Assessing building performance in residential buildings using BIM and sensor data

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Abstract

Purpose – Buildings and their use is a complex process from design to occupation. Buildings produce huge volumes of data such as building information modelling (BIM), sensor (e.g. from building management systems), occupant and building maintenance data. These data can be spread across multiple disconnected systems in numerous formats, making their combined analysis difficult. The purpose of this paper is to bring these sources of data together, to provide a more complete account of a building and, consequently, a more comprehensive basis for understanding and managing its performance.

Design/methodology/approach – Building data from a sample of newly constructed housing units were analysed, several properties were identified for the study and sensors deployed. A sensor agnostic platform for visualising real-time building performance data was developed.

Findings – Data sources from both sensor data and qualitative questionnaire were analysed and a matrix of elements affecting building performance in areas such as energy use, comfort use, integration with technology was presented. In addition, a prototype sensor visualisation platform was designed to connect in-use performance data to BIM.

Originality/value – This work presents initial findings from a post occupancy evaluation utilising sensor data. The work attempts to address the issues of BIM in-use scenarios for housing sector. A prototype was developed which can be fully developed and replicated to wider housing projects. The findings can better address how indoor thermal comfort parameters can be used to improve housing stock and even address elements such as machine learning for better buildings.

Keywords Smart buildings, Building performance, BIM for facilities Management, Sensor data

Paper type Research paper

Introduction

Maintenance and better general management of housing stock has been a national policy in the UK for several decades. An estimated 10 per cent (2.4m) of households in England are managed by housing associations and funded through government (Ministry of Housing, Communities and Local Government, 2017). Repair and maintenance of housing association properties is a routine activity as assets age and falls to organisations commissioned and managed by local authorities. Publicly funded organisations, such as social housing landlords, are under increased pressure to reduce costs of repair and maintenance activities. The three most common causes of wear and tear in buildings occur through impact from weather, occupants and moisture generated from wet areas within buildings, such as kitchens and bathrooms (Chong and Low, 2006). Such failure in buildings during use compared to initial design benchmarks can lead to a variety of issues and problems for both occupants and

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owners. By better understanding issues such as material of construction, type of occupants and how and where energy is used, there is an opportunity to investigate methodologies for understanding building performance against design recommendations and benchmarks.

Statistically significant variation in energy consumption exists even in similar dwellings (Gill *et al.*, 2011). Whilst energy consumption per household is decreasing over time, the number of households continues to increase, creating upward pressures on the increasing service demand (Department for Business, Energy and Industrial Strategy, 2018). There is an understanding and appreciation that there is still a gap in building performance, particularly in terms of energy consumption; however, it is important to manage and address such issues as building performance evaluation from an energy and carbon point of view. The impact of buildings as a contributor to climate change has been well documented, with approximately 40–50 per cent of global energy use consumed by buildings' operational energy requirements (European Commission, 2011). The built environment plays a significant part in contributing to resource depletion through material use and energy consumption. In the EU, it is responsible for 50 per cent of all extracted materials and 35 per cent of greenhouse gas emissions (GHGs) (Yoshino *et al.*, 2012). The housing sector is responsible for a big percentage of overall consumption through electricity and space heating. In addition, policy at governmental levels has not addressed such variations. A recent review by Stevenson (2019) identified four key factors that contribute to failure in improving building performance: government fail to systemically follow through on building performance initiatives, standards and policies; stakeholders such as building contractors, local authorities and housing associations operate independently of each other often with different priorities around building performance; lack of institutional engagement in the education sector around pushing building performance priorities forward as a key driver; and the potential for interdisciplinary models to embrace all members of the design team as well as the client is currently underutilised.

In the context of social housing provision, understanding the deficiencies in design, construction and commissioning processes that result in the difference between that expected and that realised in building performance is critical, as local authorities can have tens of thousands of properties to operate and manage, limited budgets and an onus to meet national targets on energy savings and the provision of good standards of housing for tenants. This research is part of a project to investigate the feasibility of a platform for performance measurement in tenanted properties by linking in-use environment data with information about the design specification, material construction and property assets and the characteristics of the tenants of the property. The research team attempt through a conceptual approach to integrate building information models (BIM) with occupant data and real-time in-use data captured through environmental sensors. BIM models can provide useful contextual information for interpreting (relating to design and construction) environmental changes and measures of energy use, and hence enable a better understanding of building performance and differences with respect to the design specification. In this paper, the researchers report on a user-centred design approach to developing a platform for integrating these datasets, comprised of understanding the stakeholder needs, outlining meaningful scenarios for integrating in-use data with BIM models, specifying a sensor infrastructure for capturing required in-use data, and designing and developing an interactive visual web tool for interacting with this data.

The development of a platform for capturing real-time data from buildings in-use to provide a more holistic view of actual building performance is described. The research presents a study that informed the platform design and data capture requirements of a social housing organisation responsible for managing over 26,700 council-owned properties, to support repair and maintenance needs. A user-centred approach to understanding information requirements for managing and organising building repairs and maintenance is described. The study presents a methodology for capturing and visualising in-use building performance data. The performance gap measurement between as designed and in-use is outside the scope of this study.

The study aims to present a framework for in-use performance data capture for a sample of domestic housing properties and a platform for visualising that data. This is achieved through the following objectives:

- enable a better understanding of building energy performance measurement in domestic housing from the perspective of large housing portfolio managers;
- understand the range of data that could be measured and captured to develop the framework; and
- develop greater understanding data driven optimisation and the role of BIM for long-term asset management.

Building performance challenges in the AEC sector

While in general the benchmarking tools or Environmental Assessment Methods (EAMs) use a recognised measure of performance, which are set against established benchmarks, there is limited analysis of buildings beyond construction stage. No reviews exist of EAMs as a successful system in the long-term or if they have a long-term impact on how a building or design performs over its lifetime. Moreover, very little academic research exists on effective use of EAMs and linking them to modern concepts such as new technology or refurbishment approaches. Purely technical approaches have been taken using EAM as a basis of developing a scientific methodology for the specification of a regulatory compliance checking system (Beach *et al.*, 2015). This is largely done due to academics investigating the validity of a tool rather than practitioners with experience giving their feedback on assessments that are carried out.

Evidence also suggests that occupied buildings usually do not perform as well as expected compared to design stage predictions (Lewry, 2015). In fact, even within the use of highly sophisticated benchmarking tools such as BREEAM (Building Research Establishment Ltd, 2019), variations exist between design stage and Post Occupancy Evaluation (POE) assessment energy consumption (LEAP, 2019). There is emerging evidence to suggest that once buildings are occupied the performance gap increases. For example, heat flow through buildings through POE exceed that at the design stage by up to 50 per cent (Gorse *et al.*, 2013). That is a significant gap and major gaps in thermal performance exist over a range of different house types from terraced to detached (LEAP, 2019).

POE serves to support learning and improvement by capturing lessons learnt from past projects (Hay *et al.*, 2018). POE tools are designed to capture the gap in actual building performance compared to intended performance. The benefits of POE are well established in research literature (Whyte and Gann, 2001; Preiser and Vischer, 2005; Vischer, 2009). Yet to date, it has been poorly adopted with only 3 per cent of British-based architectural practices regularly undertaking POE on housing projects, only 9 per cent of chartered practices offering POE to clients, and none generating revenues from POE services (Clark, 2015; The Fees Bureau and RIBA, 2015). Culture change, lack of understanding of the benefits of POE, insurance and liability issues, deregulation and the need for robust support from the professional institutes, are cited as issues to POE adoption within the industry (Hay *et al.*, 2018). This shows that despite POE's being beneficial in identifying performance gaps, there are not enough companies utilising them. Currently, there are several industry and government attempts to connect building performance activity to the new field of BIM, with the promise of linking design input directly with facilities management feedback via object-related building performance information and Geographic Information Systems (Göçer *et al.*, 2015).

In the UK, the incorporation of the principles of Government Soft Landings within BIM Level 2 through guidance in BS8536-1 gives a clear signal of a wider recognition of the value of the integration of POE in the procurement process (Hay *et al.*, 2018). Current tools for collecting data do not support learning and are mismatched with regards to industry practice (Heylighen *et al.*, 2007). If knowledge is captured, feedback mechanisms are often limited to formal documents, in the form of checkboxes and reports (Bordass and Leaman, 2005). There are very few feedback mechanisms that respond to the preferred ways in which the industry acquires knowledge that is often to prioritise the "visual" as a key value, for instance the prevalence of dashboard use in reporting (Cohen *et al.*, 2005). This coupled with the majority of feedback being concerned with performance metrics at a single point in time (often within the initial year of use), renders accounting for user appropriation of the building and seasonal change problematic (Kelly *et al.*, 2011).

Many feedback techniques focus on the technical performance of a building, a few, for example, CIBSE Energy Assessment and Reporting Methodology (TM22) (Bordass and Leaman, 2005), offer some value to the industry, but mainly in terms of identifying when energy improvements could be made in order to meet new, stricter, building regulations. An additional issue with many of these feedback techniques is that data are collected through questionnaires, including the Association of University Directors of Estates POE Guide (Association of University Directors of Estates, 2006) and Building Use Studies (Leaman and Bordass, 1993), which are aimed at the client and the users' perception, respectively. This approach tends to deliver generalised feedback that does not provide the industry with the type of information they desire, as they can only provide surface level detail with no ability to understand why respondents gave the answers they did (Bordass, 2005). A few feedback techniques have the direct intention of influencing design decisions, such as Design Quality Indicators (Gann *et al.*, 2003), soft landings (Bordass, 2005) and AMA workwear (Alexi Marmot Associates, 2008). All three tools take a broader stakeholder perspective, which includes architects and explicitly attempt to aid future designs by educating all stakeholders on the issues faced by users. They also attempt to amalgamate knowledge at multiple points in time. It is clear that feedback about buildings in-use will elicit a better understanding of how they perform in-use. However, with key challenges to existing POE's, such as lack of use, unsuitable formats and single data collection points, it is important that other mechanisms are explored to mitigate these challenges.

Building performance and housing

It is important to measure building performance in housing stock as it is a main contributor to climate change, and increasing housing demands means greater rate of construction and carbon emissions. Buildings consume 30 per cent of all energy used and associated carbon worldwide for both commercial and domestic sectors (International Energy Agency, 2018). This has led to a variety of fiscal and voluntary initiatives aimed at reducing this amount, as the increase in energy will lead to greater carbon emissions globally. At an international level with its intention to stabilise greenhouse gas (GHG) concentrations in the atmosphere at a certain level that would prevent dangerous anthropogenic interference with the climate system, two legally binding agreements were launched: Kyoto Protocol and the Paris Agreement. Kyoto Protocol is the first treaty which was introduced in 1997 to commit developed countries (who are responsible for half of global GHG emissions) to reducing their collective GHG emissions by at least 5 per cent of the 1990 level by the period 2008–2012 (United Nations Framework Convention on Climate Change, 1997). This was translated as several top down initiatives and legislative frameworks across the developed world. These include green certification tools, for designing and delivering energy efficient and sustainable buildings which have been growing in importance over the last 20 years. To achieve this, a number of benchmarking tools have been developed to enable sustainability of buildings to be measured against set criteria (Cotgrave and Riley, 2012).

The buildings are rated at design and (sometimes) post construction stage, and a certificate is awarded depending on the number of credits given. What is far from certain is how buildings behave over longer stage post occupancy and what effect do occupants have over predicted energy and carbon consumption.

According to Yoshino *et al.* (2017), one of the main factors affecting energy efficiency in buildings is the lack of knowledge of factors to determine consumption. Further to this, Yoshino *et al.* (2017) define the following six factors that influence building energy consumption: climate, building envelope, building services and energy systems, building operation and maintenance, occupant activities and behaviour and indoor environmental quality. Thus, understanding behaviour and occupant patterns is just as vital as legislative measures in terms of assessing building performance. In addition, understanding behaviour can greatly influence the area of asset information and the utilisation of BIM technologies for more effective asset management. Alwan (2016) identified much potential for employing modern technology for asset management for social housing within a BIM framework. Overall, the application of BIM frameworks for housing needs have lagged behind the commercial sector, specifically in terms of asset management and overall defects and thus building performance evaluations. Alwan and Gledson (2015) identified that green building performance can be achieved by integration of EAM into frameworks for asset management. However, such benefits are yet to be fully realised in the housing sector.

Methodology

The project began with qualitative interviews with stakeholders at the social housing partner organisation to understand current maintenance regimes. These were thematically analysed and a set of prioritised stakeholder information needs and were derived from them. Use case scenarios based on the information needs and on building design and performance industry standards were developed and tested within the project. An analysis of the building in-use data required to test the scenarios was carried out by the project team. The data were categorised according to the performance metric they were measuring, along with the feasibility of capturing them assessed by the availability of technology, precision and accuracy, and cost. From this, a sensor infrastructure for in-use monitoring was defined. A set of tenants across seven properties were recruited for the study and sensors deployed within their apartments. A sensor agnostic platform was developed that allowed data of any type (for example real-time temperature data or static occupant data) to be linked to the spatial data of the building model. Data visualisation techniques were used to display the real-time building performance data in the context of the spatial building model.

Use case scenario development

The main challenges of managing housing stock and maintenance regimes for the social housing organisation were captured through structured interviews with five stakeholder participants. These included an Environmental Sustainability Co-ordinator (P1), Technical Surveyors (P2, P3, P4) and Property Services Managers (P5). Three main areas were considered for analysis, these include: wellbeing, maintenance and energy performance. From the interviews, a set of high-level scenarios representing information needs relating to each area were identified. The scenarios covered disrepair claims, temperature, mould complaints and the overall build quality and maintenance needs. A desk review of sector practices was carried out to help supplement the issues raised with specific targets from building regulations, such as ideal light levels for wellbeing. The scenarios were refined according to the findings of the review.

Identifying data sources

For each scenario, the data sources required to capture the information were determined (e.g. room temperature), existing data sources were documented, and available sensor technologies for addressing gaps in information needs were identified. The sensor infrastructure defined to capture the gaps in data required consisted of:

- The BuildAx wireless monitoring system[1], consisting of wireless sensor units capturing temperature, light (LUX) level, humidity and passive infrared (PIR) events (1 or more in each room, reading at 5-min intervals), and a wireless hub (located in a storage room of the apartment block) for logging and transmitting the sensor readings to an external server.
- HOBO MX CO_2 logger (in the main bedroom capturing CO_2, temperature and humidity).
- Open Energy Monitor emonPi with CT sensors[2] for measuring electricity use.
- Open Energy Monitor emonPi with Optical Utility Meter LED Pulse sensors for measuring gas consumption.
- Open Energy Monitor emonPi with temperature sensors for measuring boiler radiator and hot water use.

A total of 68 sensors were deployed across seven apartments within a single apartment block, and on average data were captured for six months from each apartment.

Use case evaluation and prioritisation

A follow up workshop was held to evaluate and prioritise the use cases against sensor availability and impact on the social housing organisation maintenance requirements. In addition to P1, P2, P4 and P5, the workshop was also attended by the Housing Options Officer (P6) and Asset Information Manager (P7) from the social housing organisation; the Energy Officer (P7) from the Local Authority; Senior Energy Specialists (P8 and P9), and a Principal Energy Specialist (P10) from an independent energy foundation. During the workshop, the participants were informed of the project aims and the work that had been done to develop the use case scenarios and identify existing and potential data sources. The participants were then asked to rank the use cases in order of priority. For each use case a set of actionable advice cards were generated. Participants were asked to pick a card, discuss the card then decide how it ranked compared to the other use cases. Figure 1 provides an example of a use case with possible actionable advice that could be generated from the use case scenario.

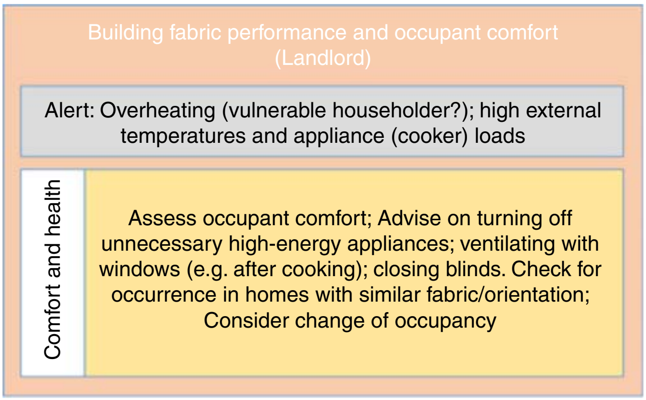

Figure 1.
Use case evaluation

Site and occupants

A newly developed site containing a mixture of one, two- and three-bedroom apartments to be managed and maintained by the social housing organisation was selected for the study. This particular site was chosen by the organisation as it was newly commissioned and they wished to understand how it performed in-use, and because a BIM had been developed for it as part of the design process. A shortlist of candidate homes for the study was produced to achieve variation in orientation, floor level and number of bedrooms. From this, seven homes were recruited to take part in the study. Tenants were invited to take part in the study by the organisation during the application process (e.g. at information events hosted by the social housing organisation) or once they began their tenancy (contacted by the housing organisation). Informed consent was acquired through a participant information sheet and signed consent form.

Prototype development

A prototype sensor visualisation platform was designed to connect in-use performance data to BIM context data to provide actionable advice for landlords and tenants for minimising repair and maintenance activities. A mock-up graphical user interface was developed with simulated data and backend processing. A web platform was required to visualise data to users. The platform was designed to be sensor agnostic and allow integration of multiple data types such as sensor, BIM occupant survey or energy performance forecast data. Figure 2 demonstrates the platform system architecture.

A second workshop was held with P1, P2, P4, P5 and P7 to evaluate the prototype. This workshop took a scenario-based design approach to exploring how different users would use the system to perform the activities identified in the use cases from the first workshop. Scenario-based design is a technique that describes how people will use a system to accomplish activities using stories to describe a sequence of actions and events that lead to an outcome (Rosson, 2009). The design phase in scenario-based design involves developing activity scenarios, then information scenarios then interaction scenarios. The scenarios were designed around two approaches for notifying staff of building defects:

(1) tenant calls social housing organisation support centre to report a problem within a property; and

(2) sensor platform notifies social housing organisation staff of a problem within a property.

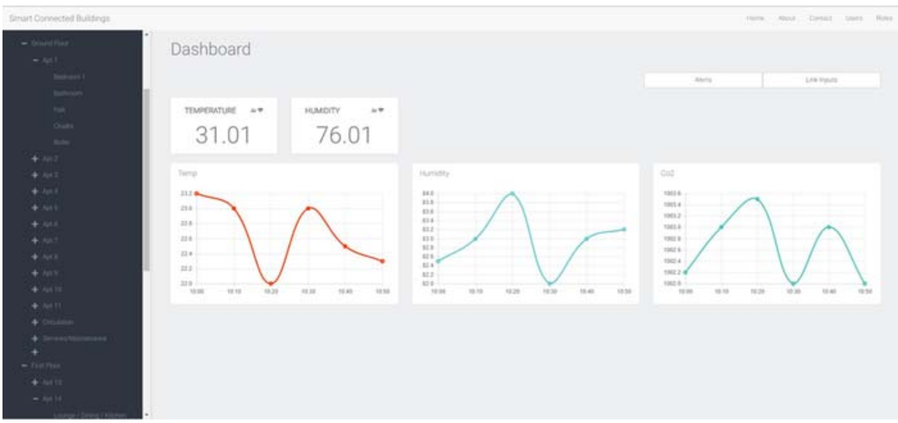

Figure 2.
The current humidity level within the data visualisation platform

The follow up process for each approach would be: Staff use prototype platform to identify potential problem cause. Staff either contact tenant and provide advice on how to resolve the problem, or staff visit the property to investigate further.

Each scenario, based on a use case, was presented to participants. Thresholds were required to be set for evaluating the second approach where the platform would notify staff if a problem occurred with an alert. For each alert scenario, the data to support that scenario was identified and a set of thresholds for that data were set to trigger the alert if the thresholds were met. For example, a to set an alert that indicates the presence of humidity within a space, a threshold upper value might be set for temperature and CO_2, and when those values combined are met an alert is triggered. The scenarios were tested and evaluated with real-time, in-use data. Methods for turning data into meaningful advice were explored, for example if the data met a threshold that could infer humidity, then what actions could be taken to prevent a negative impact to the property or occupant wellbeing. Methods such as e-mail, text message or alerts, for notifying the social housing organisation contact centre when alerts were triggered were discussed during scenario testing with workshop participants.

Findings

Use case requirements

In total, 15 use cases were identified from the initial interviews: four related to energy cost savings, eight to occupancy comfort and health and three to building performance. Cost-related use cases focussed on creating cost savings for tenants. Comfort and health use cases identified scenarios that affect occupant wellbeing such as under-heating, overheating or damp. Building performance related scenarios were designed to identify gaps in building performance design against use such as energy consumption. Figure 3 shows the data requirements that were identified to support the use cases.

During the prioritisation process humidity featured most significant as it has a direct relationship to wellbeing and maintenance. Further to this use cases relating to overheating or under-heating of properties featured next, followed by light levels. Temperature-related scenarios also relate to both maintenance and wellbeing, while light levels only relate to the wellbeing aspects of occupants. From the sensor analysis, a sensor that monitored

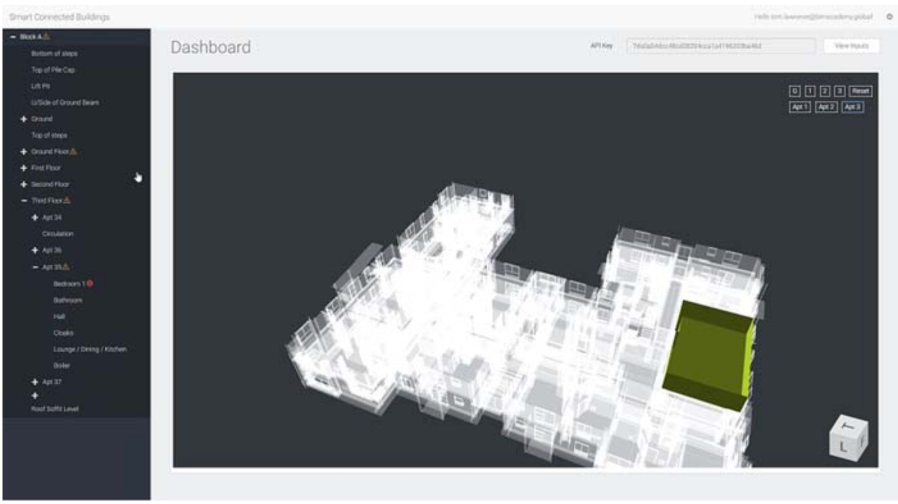

Figure 3.
Sensor visualisation platform

temperature, ambient light and humidity within one unit was identified. CO_2 sensors were used to detect if people were in the properties and if ventilation was adequate. Heating activity was monitored through clamps on the boiler to give insight into how the heating system was used. Additionally, power consumption was monitored to highlight activity such as cooking, which may generate humidity.

Sensor visualisation platform

A web-based prototype was developed linking real-time sensor data to a BIM model (Figure 4). The spaces from within the BIM model provide the navigational structure for navigating through the building, apartments and spaces within that building.

Selecting a space provides an overview of the sensor data within that space. Data can be further drilled down into by selecting a sensor to access historical data for that sensor. Figure 5 provides an overview of a selection of the sensor data outputs.

A number of challenges occurred during system development. For example, the BIM model had front doors that erroneously overlapped spaces and floors, some apartments were incorrectly numbered, floors were unclearly labelled (e.g., “top of steps”). BIM data had

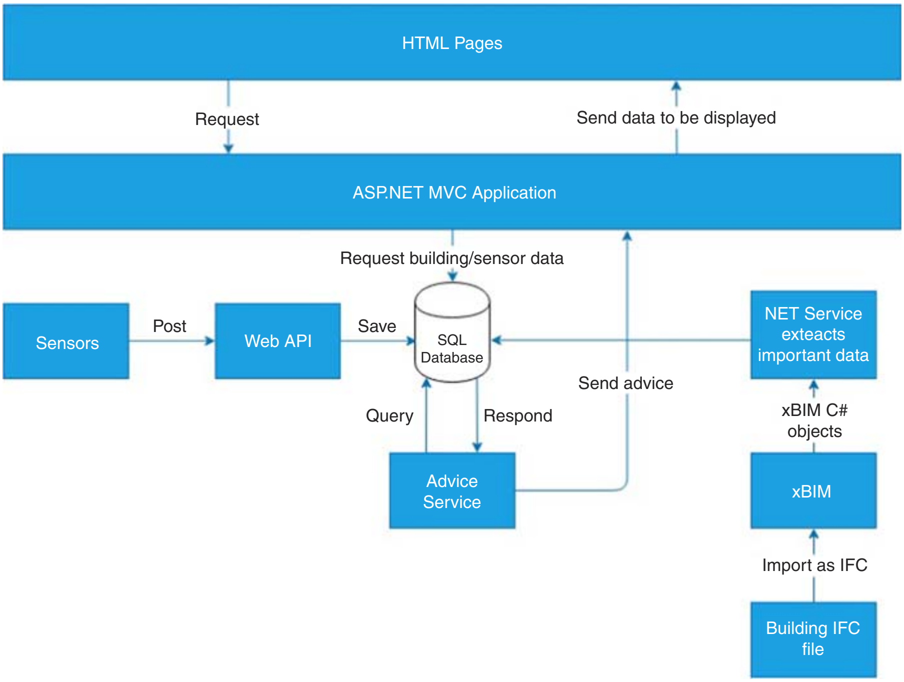

Figure 4.
Platform system architecture

Figure 5.
The sensor data linked to apartments or spaces within the BIM

to be cleaned before spaces could be correctly identified and programmatically linked to sensor data. A second problem occurred around sensor deployment, a test deployment was set up and evaluated but when the deployment was installed in multiple homes, the environment failed a stress test. This was resolved by installing each sensor network as an individual deployment with its own router on each floor of the apartments.

During the analysis stage a range of data sources (see Figure 3) were identified to support the information requirements needed to understanding building in-use performance as defined in the use case scenarios. The three use case scenarios this study focussed on were: humidity, overheating and under-heating, and light levels. The data for each use case were required to be associated with a property or a space within that property. The BIM model of the apartment block the properties were contained in was used to link other data sources to a property or space. The use of the BIM model for understanding the spatial and location details of properties is further described. Each use case scenario and the data required to support those scenarios are presented in detail.

Using BIM to understand in-use building performance data capture

The BIM model was an architectural model presented in the Autodesk Revit format by the architects of the building (Autodesk, 2019). The model was exported to the industry format for BIM data sharing which is Industry Foundation Classes (IFC) format (buildingSMART, 2019). The geometric data of the IFC were used to provide a visual representation of the building within the data visualisation dashboard. The semantic data of the IFC were used to traverse the spatial data within the model. The descriptive data within the IFC were used to provide information about spaces such as floor, apartment number and name of space, e.g. bathroom. The sensor data for each of the use case requirements were linked to apartments or spaces within the BIM. For example, tenant data could be added to an apartment and sensor data such as temperature could be added to a space, such as the bathroom (see Figure 6). The BIM model provided the navigation structure for navigating around apartment and space data. Additionally, the BIM model provided a method for visualising which room or apartment the data was connected to. Lastly warnings could be displayed next to apartment and room details or rooms could be highlighted to denote where alerts had been triggered.

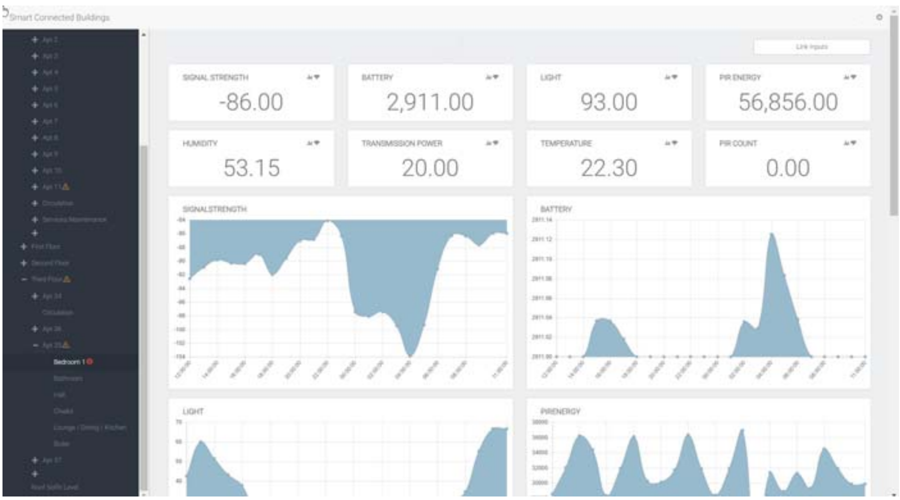

Figure 6.
Overview of a selection of the sensor data outputs

The scenario evaluation within the data visualisation dashboard provided further insights to the current approaches to addressing issues with housing stock. Currently, the social housing provider has no way of monitoring their housing stock in-use, meaning they only get notified of negative impacts on the tenants or properties when an occupant calls in to a central customer support line to raise an issue. Relying on customers to log issues using this method often means that the property is already requiring a repair. The monitoring and alert mechanism on the dashboard allows social housing landlords to quickly identify scenarios, which may cause damage to properties and intervene with advice to prevent maintenance requirements and therefore reduce the amount of responsive maintenance activities required. Further to this, the participants highlighted that the platform would allow them to identify common scenarios for damage cause allowing them to compile a library of guidance for tenants for managing homes better. This guidance could be used as a standard and shared between housing landlords to reduce the cost of reactive maintenance whilst improving the overall wellbeing and comfort of social housing tenants.

Use case scenario – humidity

The amount of moisture in the air combined with the temperature gives an indication of the humidity levels within a space at any given time. Sensors were used to capture data relating to humidity levels. The current humidity level could be viewed within the data visualisation platform (see Figure 7). Further to this it is possible to create a line graph that shows the rise and fall of humidity over a given time period.

Use case scenario – overheating and under-heating

Overheating and under-heating are subjective and relate to both the needs of the tenant and the building. Subsequently, a range of data sources were taken into account to assess the heating requirements of a space. Forecast data and standard guidance such as building regulations provide recommendations for predicted thermal comfort within buildings. Data relating to the number of tenants, age of tenants and specific tenant needs such as health conditions are captured in tenant application documents. This information provides specific detail about the temperature requirements of a tenant's dwelling. Changes in CO_2 readings and PIR data can infer as to whether anybody is present or moving within a space (although

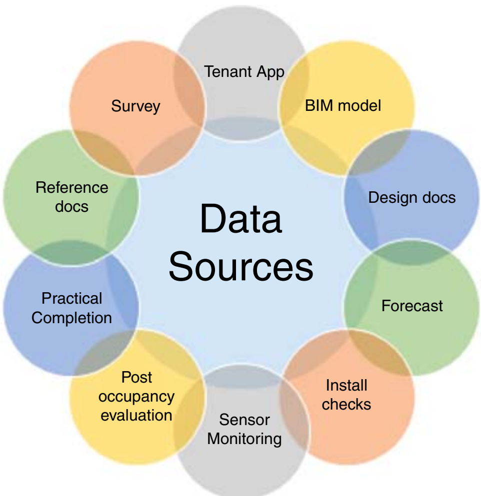

Figure 7.
Data requirements to support the use cases

these data may be inconclusive if animals exist within the dwelling). Temperature sensors can be used to predict the current temperature of a space and these data combined with other data sources can be used to identify high and low temperature thresholds for a space. These thresholds can be used to set up alerts within the data visualisation platform to notify building managers if a tenant or building is at risk due to overheating or under-heating of a space within their dwelling.

The data visualisation dashboard allows the user to view the current temperature of a space at any point in time (see Figure 7). Additionally, the user can view the temperature of a space over a given time period. Lastly, the user can set up alerts within the system to be notified when temperatures exceed threshold limits.

Use case scenario – light levels

As with overheating and under-heating, light levels are subjective to tenant requirements. For this reason, static data relating to light levels were captured within the tenant application and building regulation data. Also, similarly to overheating and under-heating, the CO_2 and PIR readings were used to detect when a space was occupied. Lastly, LUX levels were measured through the BuildAX sensors. The combination of these data sources could be used to assess the levels of light at any given time within the day and predict whether the light levels for a space were correct for a space that was occupied. Unlike temperature, light levels are also subject to whether or not the tenant has the lights turned on or off for a specific reason such as sleeping. In this case further data is required to make a more meaningful prediction as to whether or not the light levels are adequate at any given time.

As with the previous use cases, the data visualisation dashboard allows light levels to be viewed at any given time, over a period of time and for thresholds and alerts to be created if light levels are exceeded.

Discussion

The data visualisation platform provides two clear contributions to monitoring building performance and understanding factors that contribute to performance gaps. These are:

(1) the data visualisation platform and alert system provide a holistic view of building performance and occupant behaviour to enable a better understanding of building performance measurement in domestic housing from the perspective of large housing portfolio managers; and

(2) the data provides better information on asset performance that can be fed back into the design process for the production of more efficient housing stock.

The data visualisation platform provides a visualisation of sensor and other data that enables a better understanding of how buildings are performing. Common factors that affect buildings in-use can be monitored and analysed at real-time. This provides an opportunity to collate in-use data for measuring the actual performance of the building against the designed performance. For asset managers with large portfolios of buildings this provides a holistic approach to assessing building performance whilst producing some clear criteria to feedback into the building design process.

The BIM was used to organise the sensor and other data by linking it to apartments and rooms within the BIM. Climate was not considered in this study but the platform has been developed so that any data can be linked to a building, apartment, room or space. Therefore, data from existing weather Application Programming Interfaces could be linked into the system to provide further insight into the conditions that affect housing assets. The measurement of light levels requires further investigation to acknowledge tenant behaviour patterns such as only requiring light at certain times for certain activities, for example light may not be required during periods of sleep. Data such as that gathered from smart watches and other sources could be used to monitor tenant behaviour but this approach would have ethical implications outside the scope of the current study that would require further consideration. The BIM model provides additional context data such as the fabric and spatial data that can be used to calculate the performance gap between predicted and in-use performance. The work required to calculate the performance gap using in-use and as designed data are outside the scope of this project. This work complements existing work around the legislative measures already in place on building regulations by providing further methods for understanding behaviour and occupant patterns in terms of assessing building performance. Furthermore, this information could be used to develop a set of tenant guidance for better managing energy consumption, along with heating and ventilation within homes to support cost savings for tenants.

Conclusion

The study set out to understand the range of data that can be capture and measured to develop a framework for in-use performance data capture for domestic housing. The user-centred approach to understanding the current performance issues in domestic housing presents a methodology for capturing a set of use cases that provide an informed set of information requirements. Further analysis of these requirements highlighted ten key data sources for understanding in-use building performance data. These include:

(1) tenant applications;

(2) BIM model;

(3) design documents;

(4) building energy performance forecast data;

(5) installation checks;

(6) post occupancy evaluation;

(7) practical compliance checks;

(8) standard building regulations (reference documents);

(9) surveys; and

(10) sensors.

During this study 15 use cases were developed, four of which related to energy cost savings; eight to occupancy comfort and health; and three to building performance. The use cases related to humidity, overheating and under-heating and light levels were used as the building performance indicators for the study. For these use cases the use of tenant applications, forecast data, standard building regulations and survey data to set a base standard of the data requirements to evaluate building performance against were explored. Data were captured from sensors to monitor in-use building performance.

The data captured during the project provide a more holistic view to understanding building energy performance and building use across buildings, for managers of large portfolios such as social housing providers. Having access to in-use data about temperature, gas and energy usage allows building managers to make informed decisions on how best to advise tenants on their use of buildings.

The BIM model has been used in this study to organise, present and communicate the data in a visualisation platform. User evaluations of the platform demonstrated that the visualisation aspect of the data provided the user with a better understanding of tenant property data such as number of rooms, spatial layout and floor detail. These data provide additional information for building managers for analysing issues around operation and maintenance.

The project has successfully developed an approach for identifying information and data requirements for supporting key activities around the operations and maintenance of buildings. A methodology has been developed for using a using a bottom-up approach to identifying sensor requirements to supporting data and information needs. The project presents a number of opportunities for further developments that would benefit owners and managers of large building portfolios. Being able to measure real-time in-use post occupancy performance data against design would provide landlords with clear guidelines to issue to building designers and contractors for new work. User satisfaction of the building can be measured against building design and performance using the platform. Having the ability to compare user satisfaction against performance allows landlords to identify problem areas and better inform tenants how to use their buildings. Lastly using real-time in-use data provide a more valid approach to assessing energy performance whilst identifying gaps from in-use data against as designed data.

Further developments to the prototype include a 3D viewer for visualising the data inputs per apartment within the 3D apartment space. Having a 3D view will allow users to visualise where an apartment is within a block and assess environmental characteristics, such as orientation and solar gain. Currently, the system has been evaluated with a single social housing provider but further workshops are planned to evaluate the system with social housing landlords from other regions within the UK. The next phase of the research is to analyse the building fabric, infrastructure, environmental and sensor data and measure this against the energy performance data supplied in the SAP reports at design stage.

Notes

1. BuildAx Wireless monitoring system: https://github.com/digitalinteraction/openmovement/wiki/BuildAX (accessed 22 January 2019).
2. https://openenergymonitor.com/emonPi-3 (accessed 22 January 2019).

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